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Low Flow Rate Sharp Cut Impactors for Indoor Air Sampling: Design and Calibration

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Two single round nozzle impactors have been developed for use in Harvard's indoor air pollution health study. Both impactors operate at flow rates of 4 L/m and are nearly identical, differing only in their cut sizes of 2.5 μm and 10 μm aerodynamic diameters. Two identical cascaded stages of the same cut size are used to obtain sharp cut-off characteristics. The particles are deposited on impaction plates made of oil impregnated, porous material to reduce particle bounce and are discarded. Only the particles collected on the afterfilter are analyzed. Special care has been taken to collect the particles uniformly on the afterfilter to aid in particle analysis.

The impactors were calibrated with a vibrating orifice monodisperse aerosol generator. However, due to the sharp cut of the impactors, doublets and triplets in the calibration aerosols, even in small quantities, gave erroneous calibration curves. Therefore, the number of doublets and triplets in the challenging aerosols were measured and appropriate corrections made to the calibration curves.

Inertial impactors are popular instruments for the collection and size classification of airborne particles. Their popularity stems from their ability to classify particles by aerodynamic diameter, an important parameter in aerosol studies, and for their ability to make sharp particle fractions (cuts) at precisely known diameters. This has resulted in impactors capable of collecting particles on sampling substrates with very specific and well defined particle size ranges.

When sampling particles for subsequent chemical/elemental analysis and possible association with human health effect, characterizing reliable size separation is important. Size fractionation of deposited particles occurs in the respiratory tract during inspiration. Further, physical and chemical processes result in bi- or tri-modal distribution of suspended particles in the atmosphere. Because alkaline particles tend to be greater than 3 μm in diameter and acidic particles tend to be less than 1 μm, a sharp size separation in this range would be desired to prevent neutralization of acidic aerosols collected on a filter. Further the distinct separation of particle mass by size permits source resolution by multivariate statistical analysis techniques using the elemental and chemical composition of the "fine fraction" particle mass. The Harvard Air Pollution Health Study has collected size fractionated ambient aerosols in each of the study cities since 1979 using virtual dichotomous impactors.[1]

For these biological and physical reasons, an impactor was developed for sampling airborne particles in the residential indoor environments. The impactor provides a sharp size separation at either 2.5 μm or 10 μm and results in uniform deposition of particles on filters (Teflon, quartz) selected for subsequent mass, chemical and/or elemental analysis. This paper describes the design and calibration of the particle impactor used in Harvard's Indoor Air Pollution Health study.[2]

Two versions of the impactor were developed; one with a particle cutsize of 2.5 μm aerodynamic diameter and the other with a cutsize of 10 μm, both at flow rates of 4 L/m. The particles collected on the impaction plates are discarded and not analyzed. The particles of interest, i.e. those less than the cut size, are uniformly deposited on afterfilters to be analyzed for mass and elemental composition.

Special care was taken in the design of the impactor to obtain as sharp a cut as possible at the desired particle size. This was done to provide comparability to the fine fraction particles collected with dichotomous samplers operated at central monitoring sites in each of the six communities. However, due to the sharp cut, the impactor was difficult to calibrate if the calibrating aerosols were not perfectly monodisperse. Calibrating with a vibrating orifice monodispersed aerosol generator (VOMAG, TSI, Inc. Model 3050, St. Paul, MN) gave erroneous results, due to the doublets and triplets in the challenging aerosol, even though they were low in number. Therefore, the number of multiple particles had to be measured and the impactor calibration corrected accordingly. This procedure is described in a later section.

Impactor Design

The design criteria for the impactor was rather simple; it had to provide a sharp classification at the design cutpoints of 2.5 or 10 μm aerodynamic diameter at a flow rate of 4 L/m and collect all penetrating particles uniformly on an afterfilter. For the design described here, the filter holder had to accommodate a 2 × 2-in. plastic filter slide containing a 37-mm diameter filter. However, any 37-mm filter could be used with a slight modification to the filter holder.

A schematic diagram of the impactor is shown in Figure 1, and photographs of the impactor parts are shown in Figure 2. For either cut size, two identical cascade stages have been used for two reasons. First, it has been shown that the combined particle cutoff characteristic of two stages with the same cutsize is sharper than for a single stage.[3] Second, if any particles do bounce from the first stage due to overloading, they should be collected on the second stage with the net result being an impactor with very little, if any, particle bounce onto the afterfilter. To further reduce particle bounce, the impactor substrates are oil-impregnated porous metal plates.[4] In practice light mineral oil is used. The oil provides a sticky surface from which the particles will not easily bounce, and the oil will wick up through the deposit to continually provide a sticky surface to incoming particles. In this manner, overloading problems do not occur as long as the deposit does not become too close to the exit of the nozzle.

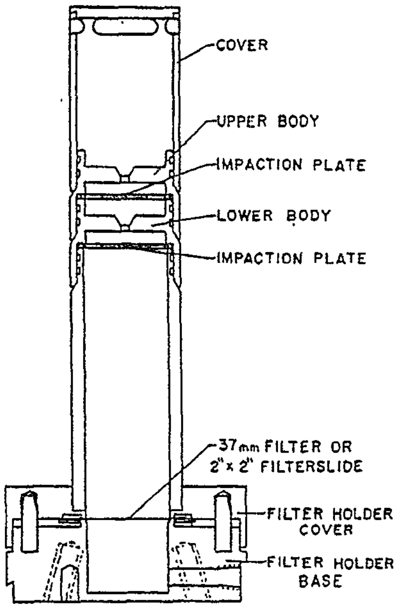

Figure 1. Schematic diagram of indoor air sampling impactor.

The filter holder consists of a base and cover that press a plastic filter slide between two gaskets. Two over-center draw latches hold the filter assembly together. The lower impaction plate sits directly on the tube extending above the filter holder and is held in place by the body containing the nozzle which slips onto the tube. The upper stage is identical to the lower stage and is assembled in the same manner. A cover slides onto the upper body to complete the impactor assembly. Important parameters of the impactor are given in Table 1. The impactor nozzle diameters were initially designed from theory[5] and then adjusted slightly after calibration to achieve the exact desired cut points.

Calibration

The impactors were calibrated using monodispersed liquid and solid particles generated with a VOMAG.[6] The liquid particles were oleic acid with a uranine dye tracer and the solid particles were ammonium fluorescein. The solid particles were used primarily in the impactor collection efficiency tests while the liquid particles were used in the particle loss studies. Both the uranine and ammonium fluorescein are fluorescent dyes. The use of ammonium fluorescein as a test aerosol and a description of its pertinent properties are described by Stober and Flachsbart[7] and Vanderpool and Rubow.[8] A fluorescent uranine dye tracer was added to the oleic acid to enable easy detection of where the particles are collected.[9] This is accomplished by passing monodispersed particles through the impactor and then washing the particles from various parts of the impactor with 0.001 N sodium hydroxide for the case of the liquid particles or 0.1 N ammonium hydroxide solution for the solid particles. The washes are then analyzed for fluorescent dye content with a fluorometer. By knowing the quantity of wash solution and the dye concentration in each wash, the relative amount of particles at all locations can be measured. In this manner, the collection efficiency curves and interstage losses can be determined.

Table I. Design parameters and cutoff diameters of the impactors in the MST indoor air sampler.

Nominal cutoff diameters, μm	2.5	10
Nozzle diameter, cm	0.244	0.620
S/W	2.0	0.86
Re	2140	900
Cutoff diameter, μm		
Theoretical	2.52	10.4
Experimental	2.52	9.8

When using the VOMAG, some doublets (particles with twice the volume as the particle size being generated), triplets, etc. are generated. Although the numbers of such multiplets may be small, their presence must be taken into consideration when using the dye tracer technique, since the quantity of dye in a doublet will give the indication of two particles of the generated size being collected rather than one particle with twice the volume. The impaction characteristics of singlets and doublets are obviously different.

The technique used to make corrections for multiplets was to monitor the number of particles of each size with a TSI Model 33 aerodynamic particle sizer (APS)[10] and to reduce the measured collection efficiency accordingly. To achieve the correction, the calibration is started with particles of size such that the multiplets are collected with 100 percent efficiency, and each subsequent calibration performed with slightly smaller particles. In this manner of developing the efficiency curve, the collection efficiency of the multiplets is always known and can be backed out of the calibration.

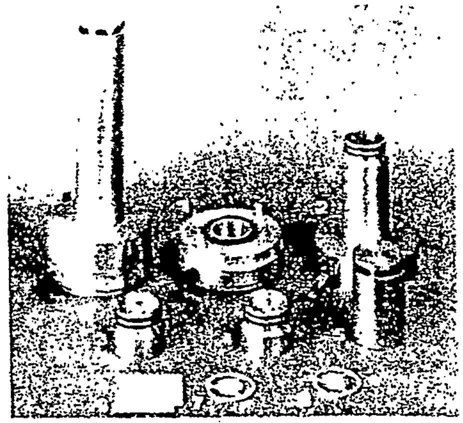

Figure 2. Indoor air sampling impactor: 1. Base and afterfilter holder; 2. Body with filter hold down clamps; 3 and 4. Nozzles; 5. Inlet; 6. Afterfilter in 2" × 2" filter slide; 7 and 8. Impaction plates; upper left: assembled impactor.

The measured efficiency is a function of the contribution of the singlets and each of the multiplet particle sizes. For a test aerosol consisting of primary (singlets), doublets and triplets, the measured efficiency, E_m, is given by

$$E_m = f_1E_1 + f_2E_2 + f_3E_3 \quad (1)$$

where f_1, f_2 and f_3 are the volume fractions of the singlets, doublets and triplets in the test aerosol and E_1, E_2 and E_3 are the actual particle collection efficiency for the singlets, doublets and triplets. The collection efficiency of the singlets, E_1, can be computed from Equation 2,

$$E_1 = \frac{E_m - f_2E_2 - f_3E_3}{f_1} \quad (2)$$

providing the collection efficiency for the larger particle sizes and the volume fraction of each aerosol type are known.

For example, assume that a particle size of 2.1 μm aerodynamic diameter has been generated and 11.3 percent are collected on the filter and 88.7 percent on the impaction plate. Further, assume that there are, on a number basis, 4.5 and 0.5 percent doublets (2.65-μm diameter) and triplets (3.03-μm diameter) respectively. Without correcting for the multiplets, the calibration curve (middle curve in Figure 3) shows the 2.1-μm particles being collected with an 11.3 percent efficiency. However, the 2.65-μm diameter particles are collected at 95 percent efficiency, and the quantity of particles on the impaction plate should be reduced by 8.1 percent. Furthermore, the 3.03-μm diameter particles are collected at 99 percent, and thus, these particles contribute an additional 1.4 percent to the measured collection of particles on the impaction plate.

Therefore, the collection efficiency of 2.1-μm diameter particles is actually only 1.8 percent instead of the 11.3 percent originally thought. The correct calibration curve is, therefore, the solid line in Figure 3 and not the middle dashed line which would be obtained if no corrections were made. It is of interest to note that the correction is only important for the low values of efficiency and becomes very critical for impactors with sharp classification characteristics.

The amount of correction, of course, depends upon the fraction of particles that are multiplets. As shown for the above example in Figure 3, 5 percent multiplets substantially alter the collection efficiency curve for efficiencies less than 20 percent. If the number of multiplets drops to 2 percent, the correction is small, as shown by the curve labeled 1.8 percent doublets and 0.2 percent triplets in Figure 3. Conversely if the multiplets increase to 10 percent (also shown in Figure 3), the correction becomes quite large, giving the indication of an efficiency curve with a large "tail" at the lower efficiencies when actually only a small tail exists in the "true" collection efficiency curve.

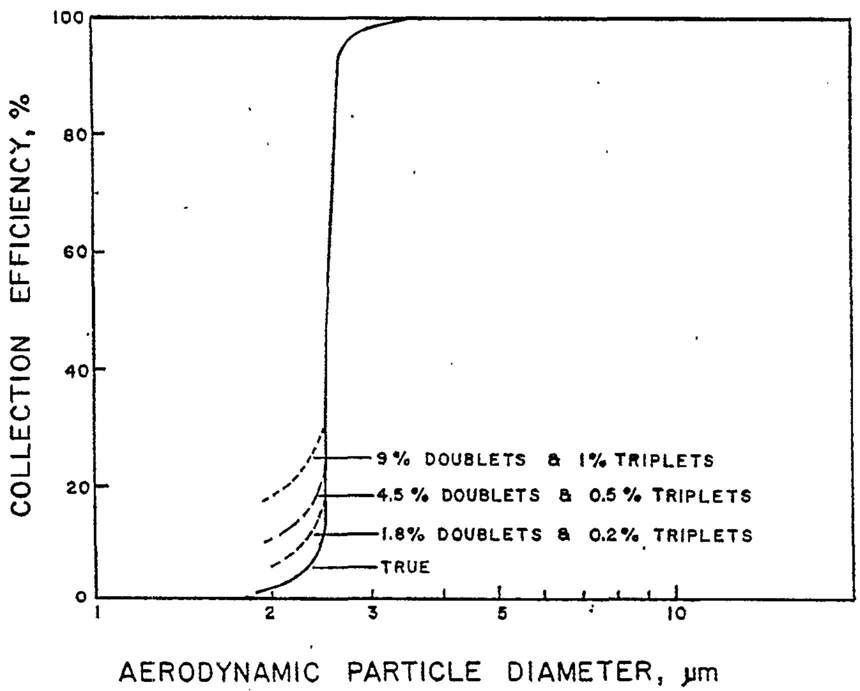

Figure 3. Effect of calibration aerosol doublets and triplets on experimentally determined efficiency curve.

The efficiency curves determined with this technique are shown in Figure 4 for both the 2.5 and 10-μm cut point impactors as dashed lines. The corresponding theoretical efficiency curves[5] are shown as solid lines. Inspection of these curves shows close agreement between theory and experimental results. If the sharpness of cut is defined by the geometric standard deviation (σ_g), where the σ_g is equal to the square root of the ratio of the particle diameter corresponding to the 84.1 percent collection efficiency to the diameter at an efficiency of 15.9 percent, it is found to be 1.02 and 1.11 for the 2.5 and 10-μm curves, respectively.

As shown in Figure 3, the multiplet correction influences the shape of the collection efficiency curve more than the 50 percent cutpoint when the impactor has sharp classification characteristics. However, for impactors which do not have sharp classification characteristics, the multiplet correction

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can also effect the 50 percent cutpoint. For example, if the sharpness of cut of an impactor efficiency curve is characterized by a geometric standard deviation of 1.6, the 50 percent cutpoint would be decreased by about 5 percent if there were 9 percent doublets. Although this is a small shift in the efficiency curve, it is a correction that should be considered when calibrating impactors with monodisperse aerosols.

Interstage Losses

Interstage losses are defined as the fraction of particles of a particular size that are collected at any point other than the impaction plate or afterfilter. Since the losses are a weak function of particle size, the losses at only a few particle sizes were measured.

Afterfilter Deposit Uniformity

One of the design criteria for the impactor was for the particles to be uniformly deposited on the afterfilter. Uniformity was checked by dividing the filter into five annular areas and measuring the dye concentration per unit area from the particles washed from the filter segments.

Uniformity of the particle deposit on the afterfilter was achieved by allowing adequate distance between the second stage impaction plate and the filter. It was found that 2 cm was sufficient for uniformity to be achieved with the 2.5-μm cut impactor with 4 percent variation which was the approximate uncertainty in the uniformity measurement technique. For the 10-μm cut impactor, the deposit on the afterfilter was not uniform with the 2-cm length. Therefore, the final

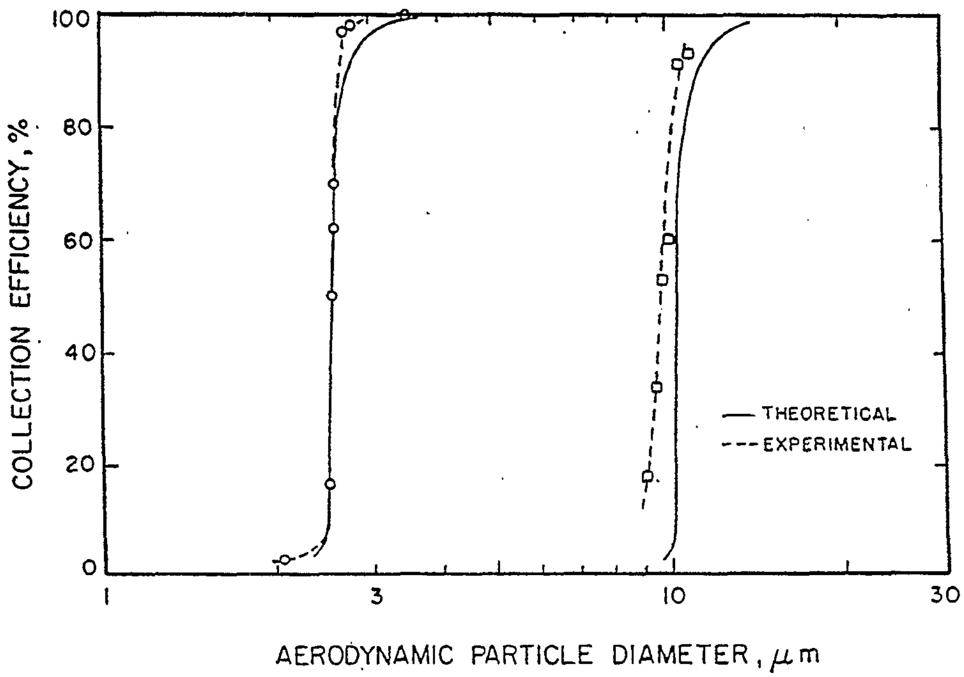

Figure 4. Theoretically and experimentally determined collection efficiency curves for the 2.5 and 10 μm cutpoint sampler.

The fraction of particles lost is measured in exactly the same manner as the fraction collected on the impaction plate; i.e., the internal surfaces are washed with known amounts of 0.001 N sodium hydroxide. The resulting dye concentration measured with a fluorometer provides good information on the fraction of particles lost.

Losses for three particle sizes of 2.0, 2.5 and 2.7 μm diameter were found to be 0.2 percent, 0.2 percent and 0.1 percent, respectively, for the 2.5-μm cut size impactor. Since losses near the cut size are expected to be the largest, the losses for this impactor are negligible.

Losses in the 10-μm cut size impactor were measured at 9.3 μm diameter and found to be 0.07 percent. Since losses were so small at this size, no other loss tests were performed and losses in the 10-μm cut impactor are considered negligible as well.

design, as shown in Figure 2, has a tube length of 10.5 cm. This length is more than sufficient to achieve a uniform particle deposit on the afterfilter in the 2.5-μm version and provides adequate uniformity for the 10-μm version.

Conclusions

An impactor operating at a flow rate of 4 L/m for indoor air sampling has been developed. Two versions were designed; one with a cut size of 2.5 μm and one with a cut size at 10 μm. The particles larger than the cut size were removed from the air stream and not used, while the smaller particles were collected on an afterfilter. The afterfilters are subsequently analyzed for mass gain and/or chemical composition. Two stages of the same cut size were used in a cascade fashion for both versions of the impactor to minimize parti-

cle bounce problems. The use of oiled porous impaction plates further reduced particle bounce. Calibration of both versions of the impactor showed sharp cutoff characteristics, low interstage losses and a uniform deposit on the afterfilter. To increase the rate of particle collection, two new impactors are being developed with increased flow rates (10 L/m) while keeping the cut sizes the same (2.5 μm and 10 μm diameter).

References

1. J. D. Spengler, G. D. Thurston, "Mass and elemental composition of fine and coarse particles in six cities," *JAPCA* 33: 1162 (1983).
2. J. D. Spengler, M. P. Reed, E. Lebret, B. H. Chang, J. H. Ware, F. E. Speizer, B. G. Ferris, Jr., "Harvard's Indoor Air Pollution/Health Study," presented at 79th APCA Annual Meeting, June 1986.
3. V. A. Marple, K. L. Rubow, "Aerodynamic particle size calibration of optical particle counters," *J. Aerosol Sci.* 7: 425 (1976).
4. G. P. Reischl, W. John, "The collection efficiency of impaction surfaces: a new impaction surface," *Staub—Reinhalt. Luft* 38: 55 (1978).
5. D. J. Rader, V. A. Marple, "Effect of ultra-stokesian drag and particle interception on impaction characteristics," *Aerosol Sci. Technol.* 4: 141 (1985).
6. R. N. Berglund, B. Y. H. Liu, "Generation of monodisperse aerosol standards," *Environ. Sci. Technol.* 7: 147 (1973).
7. W. Stober, H. Flachsbart, "An evaluation of nebulized ammonium fluorescein as a laboratory aerosol," *Atmos. Environ.* 7: 737 (1973).
8. R. W. Vanderpool, K. L. Rubow, "Generation of large, solid, monodisperse calibration aerosols," *Aerosol Sci. Technol.* (to be published).
9. K. Willeke, "Performance of the slotted impactor," *Am. Ind. Hyg. Assoc. J.* 36: 683 (1975).
10. J. K. Agarwal, R. J. Remiarz, F. R. Quant, G. J. Sem, "Real-time aerodynamic particle size analyzer," *J. Aerosol Sci.* 13: 222 (1982).

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